Presented at the 7th International Workshop on Atmospheric Icing of Structures (IWAIS'96),
Chicoutimi, Quebec, Canada, June 3–6, 1996

Atmospheric Icing and Tower Collapse in the United States

N. D. Mulherin
U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road, Hanover, New Hampshire, USA

Abstract

CRREL has established a database of communication tower collapses (TV, AM, FM, CATV, microwave, cellular, and so forth) that have occurred in the United States due to atmospheric ice accretion. The information was compiled primarily from newspapers articles and telephone interviews, but also from a multitude of other sources. The database currently lists 140 such failures of towers, ranging in height from 40 to 2000 ft above ground level (agl), dating as far back as 1959. For each case, I am compiling the following information: 1) structural characteristics of the tower, 2) the geographic location and topography, 3) a description of the collapse, 4) concurrent weather, and 5) damage. The database is growing and therefore not fully analyzed. In many cases, data in all these topic areas do not exist or are not available; some data I have yet to obtain. Trends in the current information are presented.

Keywords

Communication tower, Glaze, Ice accretion, Icing, Radio and television, Rime, Tower collapse, Tower failure

1. Introduction

A radio or telecommunication mast is composed of 1) an antenna, for sending or receiving electromagnetic signals such as TV, AM, FM, CATV, VHF, microwave, cellular, etc., and 2) its supporting structure, one or more steel towers with guy cables and anchors (though some towers are freestanding). This paper will use the term "tower" to refer to both an antenna and its supporting structures as a unit.

While established engineering practice requires that certain minimum loads be considered in their design, communication towers collapse for a variety of reasons. Some collapses can be attributed to human error, such as flawed design or construction, lack of regular maintenance, accidental damage, and so forth. Other causes include malicious mischief, metal fatigue, and the use of substandard material. However, most failures are caused by rare natural events (for example, blizzard, hurricane, tornado, and earthquake).

Ice storms are a natural hazard that cause towers to collapse. Ice can build up on towers from liquid precipitation such as freezing rain or drizzle, or from wet snow (precipitational icing), or from wind-transported, supercooled fog droplets that freeze when they contact a structure (in-cloud icing). Both types of icing are referred to as atmospheric icing.

Atmospheric icing is a design consideration for the radio and telecommunications industries. For optimum signal transmission or reception, antennas are typically elevated and exposed. These are prime conditions for wind loading and ice accumulation. Ice buildup on towers causes signal interference, structural fatigue from dynamic loading, guy wire stretch, ice-fall damage when the ice sheds, and complete tower failure. This paper describes a database created at CRREL to document icing-related tower failures in the United States. In this context, a tower failure is defined as the collapse of at least the antenna of a communication mast and can include the partial or total collapse of its supporting tower.

2. Sources of Information

While catastrophic failure of a communication tower is relatively rare, it occurs perhaps more often than is generally known or acknowledged. There is no organization that is responsible for maintaining a history of tower failures, icing-related or otherwise. I assembled the information in this database over approximately a decade of research, and believe it to be the most complete list of icing-related failures in existence. I was aided by individuals who shared with me their own unpublished lists of tower failures (Goudy 1992, Marshall 1992, Monts 1992, Laiho 1993). Their lists contained more well-known failures of towers throughout the world, from any and all causes. Duvall (1993) provided a list of 14 failures for which was known the maximum dis-

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1996**	2. REPORT TYPE	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Atmospheric Icing and Tower Collapse in the United States**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Army Cold Regions Research and Engineering Laboratory,72 Lyme Road,Hanover,NH,03755**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

CRREL has established a database of communication tower collapses (TV, AM, FM, CATV, microwave, cellular, and so forth) that have occurred in the United States due to atmospheric ice accretion. The information was compiled primarily from newspapers articles and telephone interviews, but also from a multitude of other sources. The database currently lists 140 such failures of towers, ranging in height from 40 to 2000 ft above ground level (agl), dating as far back as 1959. For each case, I am compiling the following information: 1) structural characteristics of the tower, 2) the geographic location and topography, 3) a description of the collapse, 4) concurrent weather, and 5) damage. The database is growing and therefore not fully analyzed. In many cases, data in all these topic areas do not exist or are not available; some data I have yet to obtain. Trends in the current information are presented.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**11**	

tance that debris landed from the tower base. From these lists, I extracted only those in the U.S that were icing related and began researching each one in more detail. Much of my information I obtained from interviews with station owners, transmitter engineers, tower designers, fabricators, and builders who had some personal knowledge of the events (telephone interviews have been completed for approximately 60% of the cases). These contacts led, in turn, to information on a great many more failures that were not widely known about. The survey form that I completed during each telephone interview appears in the Appendix.

I supplemented this first- and second-hand knowledge with storm records from the National Climatic Data Center (NCDC 1960–1994, NOAA 1959–1995) (for approximately 60% of the cases) and newspaper articles from state and local libraries (for approximately 70% of cases). When other sources were lacking, I obtained the names of towers, their coordinates, heights, or ground elevations from the U.S. Geological Survey's digital database of place names appearing on their $7^1/_2$-min quadrangle maps (USGS 1993) or from the National Oceanic and Atmospheric Administration's Digital Obstructions File (O'Brien 1994). NOAA's DOF lists all types of obstructions to aviation. Besides tall buildings, smokestacks, catenaries, grain elevators, and so forth, it lists 43,467 communication towers (or clusters of towers) in the 50 states.

3. Trends Derived from the Major Topics of the Database

To date, I have confirmed approximately 140 tower collapses in the United States, dating back to 1959, that occurred with a buildup of atmospheric ice on the structure. These are listed as Table 1. Approximately 15 more reports are, as yet, unconfirmed. The towers include television, radio (FM, AM, and two-way), and microwave receivers and transmitters, ranging in height from 40 to 2000 ft agl. I have obtained varying amounts data for each failure in the form of 1) structural characteristics of the tower, 2) its geographic location, 3) a description of the collapse, 4) concurrent weather, and 5) resulting damage. The picture is constantly changing as new failures occur and as past failures are added to the database; however, I will describe certain trends in the data from each of these main topics and summarize the current information.

3.1 Structural Characteristics

Communication towers are usually triangular in cross section (though some are rectangular), with legs and cross bracing constructed of solid rod, tubular, or angular galvanized steel. They are usually supported against lateral loads by a network of guy cables attached to each of the legs at one or several elevations. The guys radiate downward to sets of three anchors in the ground. Depending on the tower's height and design loads, single, double, triple, or quadruple sets of three anchors provide ground attachment, each set being buried a greater radial distance from the tower's base. Although most towers have a constant horizontal cross section over their entire height, many towers are designed with either a continuous taper or with intermittent tapered sections from bottom to top. Freestanding towers (without guy cables and anchors) are nearly always tapered, of heavier construction, more expensive to build, and therefore not as numerous as guyed towers. Freestanding towers require less land area so they may be used at sites where land costs are high or space is limited.

Only one of the failures is known to have involved a freestanding tower, a 310-ft, two-way-radio tower that was approximately 17 years old. The average tower age, for the 77 cases in which that information is available, is 11.5 years, and the standard deviation is 10 years. Of those cases in which the structure cross section is known, most had a constant cross section, but a few tapered.

Communication towers usually serve many functions. Many stations broadcast both FM and AM frequencies from the same tower, and sometimes a television signal. Often a television station leases tower space to a separate radio station and any number of two-way user groups. For this report, I have classified each tower according to its primary use. Figure 1 shows the distribution of the tower types in this database. The largest number of failures involved television and FM broadcasters, and two-way transmitters; their total numbers are almost the same. Failures of AM broadcast and cable television receiver towers are noticeably fewer. The numbers somewhat reflect the much greater incidence of certain tower types, with the exception of two-way towers. Towers dedicated to AM or cable television are considerably less numerous than the other three types. Although two-way towers (including paging and mobile telephone towers) vastly outnumber television and FM towers, their collapse affects fewer people so perhaps there is less attention paid to their demise. We are less likely to find old newspaper articles and people do not recall as readily when a private company loses its two-way tower during a storm. For these reasons, I believe that failures of two-way towers are vastly underreported and therefore not well represented by these data. I have several reports of such failures that I have not been able to confirm, and therefore have not included in this summary.

A histogram showing the heights of 121 of the towers appears as Figure 2. Nearly a third, or 39 of the towers, were 300 ft tall or less. A similar number (43 of 121) were between 300 and 601 ft tall. One-fifth (24 of

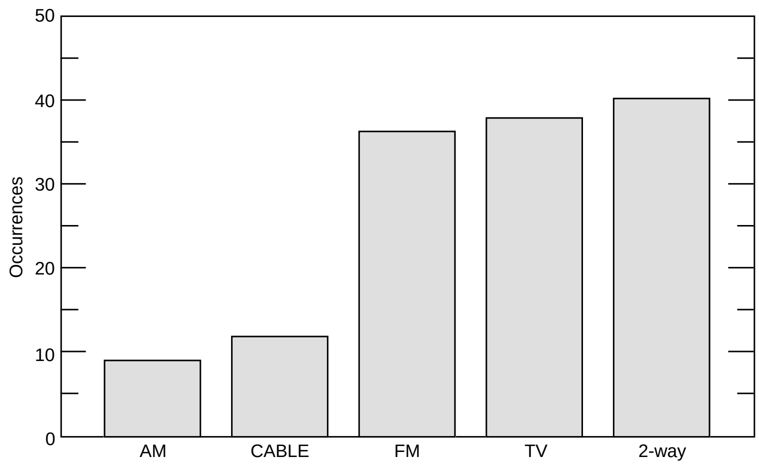


Figure 1. Histogram of failures by tower type.

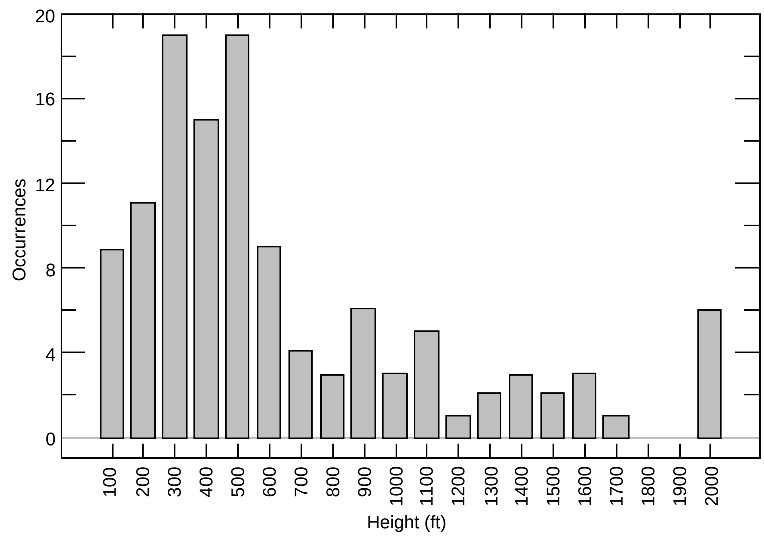


Figure 2. Histogram of failures by tower height above ground level.

121) were taller than 1000 ft. The mean and median heights for the 121 cases were 607 and 480 ft, respectively.

Other structural information in my database includes, when available, the tower's wind and ice design loads, face width, anchor pattern, number of guy levels, and other transmitting or receiving equipment on the tower.

2.2 Geographic Location and Topography

Figure 3 shows where icing failures have occurred across the U.S. The numeral shown in each state indicates the number of separate storms that caused all the failures within that state. For example, three towers fell in two separate storms in Texas; one in 1960 and two more in a 1978 storm. The map symbols indicate the height ranges of these towers.

The data indicate that icing-related tower failures have occurred almost exclusively east of the Rocky Mountains and 66% (93 of 140) occurred north of latitude N37° (i.e., north of Arizona, Oklahoma, Arkansas, Tennessee, and North Carolina). The most failures have occurred in the midwestern states and the Appalachian highlands. There have been at least six failures resulting from at least four separate storms in each of North and South Dakota, Minnesota, Iowa, Nebraska, and Kansas. Six failures have occurred in Illinois, although from only two storms.

The many failures in the southern Appalachian uplands of North and South Carolina and Alabama were generally the result of fewer storms per state, compared with those in the upper Midwest. Those southern storms were generally more widespread and severe. In February 1994, the southeastern U.S. was hit by an unusually devastating ice storm (Lott and Ross 1994). The storm caused over $3 billion in damages and cleanup costs, and at least nine deaths. An estimated 2.2 million people in 11 states were without power at some point during the storm and, in some locations, power was not restored for a month (FEMA 1994). The lowland delta region of northwestern Mississippi, shown as a hatched area in Figure 3, was especially hard hit. Nearly every communication tower in Bolivar and Washington coun-

Table 1: Current list of icing-related tower failures in the U.S.

No.	Mo	Dy	Yr	Tower name	Type	Location		Height (ft)
1	11	28	59	WBRV	AM	Boonville	NY	250
2	12	7	60		TV	Marfa	TX	
3	12	8	60	KSWS	TV	CapRock	NM	1610
4			61	WCDC	TV	Adams	MA	
5	2	26	61	Antenna Systems	CT	Potsdam	NY	400
6	2	26	61	Canton FD	2W	Canton	NY	
7	2	23	62		TV		KY	
8	1	16	67	KSDN	AM	Aberdeen	SD	270
9	1	26	67	WICD	TV	Homer	IL	1335
10	1	26	67	Illini Elec	2W	Champaign	IL	310
11	4	30	67	KXMB	TV	St. Anthony	ND	882
12	4	30	67	KEM Elec Co-op	2W	Linton	ND	370
13	2	6	69	NE Road Dept	2W	Flats	NE	300
14	2	26	69	KDIX	TV	Dickinson	ND	50
15	2	26	69	KXMB	TV	St. Anthony	ND	876
16	2	4	71	WDOE	AM	Dunkirk	NY	194
17	2	23	71	WNPE	TV	Copenhagen	NY	925
18	2	28	71	KOIN	TV	Portland	OR	1000
19	2	28	71	KOIN	FM	Portland	OR	750
20	12	16	72	Civil Defense	2W	Clarks Knob	PA	60
21	1	8	73	Farmers Fertilizer	2W	Lovington	NM	
22	12	3	73	MidKansas	CT	Junction City	KS	500
23	12	3	73	MidKansas	CT	Junction City	KS	500
24	12	3	73	KS Hwy Patrol	2W	Clay Center	KS	245
25	12	4	73	KJCK	FM	Junction City	KS	500
26	12	4	73	KJCK	AM	Junction City	KS	500
27	12	4	73	KMKF	FM	Manhattan	KS	60
28	12	4	73	KRNT	TV	Alleman	IA	2000
29	12	4	73	KIFG	FM	Iowa Falls	IA	237
30	12	4	73	Midwest Elec	2W	Des Moines	IA	100
31	12	4	73	Farm Bureau	2W	Eldora	IA	230
32	12	17	73	WKOX	AM	Framingham	MA	206
33	1	11	75	Renville Cnty	CT	Bird Island	MN	550
34	1	11	75	K & K	CT	Devils Lake	ND	500
35	1	11	75	KSFY/KELO	TV	Rowena	SD	1985
36	3	23	75	KLOH	FM	Jasper	MN	385
37	3	27	75	KRSW	FM	Chandler	MN	703
38	3	27	75	Watowan	CT	Godahl	MN	620
39	3	27	75	KXON	TV	Salem	SD	1569
40	3	27	75	KXEL	FM	Waterloo	IA	600
41	3	27	75	IA Safety Dept	2W	Storm Lake	IA	330
42	3	27	75	old tower	2W	Storm Lake	IA	320
43	12	21	75	NE Road Dept	2W	Tryon	NE	300
44	3	4	76	WTMB	FM	Tomah	WI	406
45	11	8	77	KDLO	TV	Garden City	SD	1405
46	11	9	77	KRSW/KLOH	FM	Chandler	MN	700
47	1	15	78	WKOX	FM	Framingham	MA	450
48	2	6	78	KTNE	TV	Alliance	NE	1499
49	2	10	78	KLOE	TV	Goodland	KS	790
50	2	12	78				TX	
51	2	12	78				TX	
52	3	25	78	WAND	TV	Argenta	IL	1314
53	3	26	78	WJPT	TV	Bluffs	IL	1588
54	3	26	78	WCIA	TV	Dewitt	IL	303
55	3	26	78	Sammons	CT	Jacksonville	IL	440
56	12	28	82	Fulda Cable	TV	Fulda	MN	126
57	1	20	83	East MS Comm	2W	Meridian	MS	300
58	1	21	83	WAGI	FM	Forest City	NC	606
59	1	21	83	repeater tower	2W	Forest City	NC	300
60	1	21	83	WQNS	FM	Clyde	NC	150
61	1	21	83	WESC	TV	Caesars Head	SC	1284
62	1	21	83	WMUU	FM	Greenville	SC	200
63	1	21	83	radio tower #1	2W	Red Mountain	AL	
64	1	21	83	radio tower #2	2W	Red Mountain	AL	
65	1	21	83	radio tower #3	2W	Red Mountain	AL	
66	1	21	83	radio tower	2W	Birmingham	AL	
67	1	21	83	radio tower #1	2W	Dbl Oak Mt.	AL	
68	1	21	83	radio tower #2	2W	Dbl Oak Mt.	AL	
69	1	21	83	radio tower #3	2W	Dbl Oak Mt.	AL	
70	1	21	83			Calera	AL	
71	1	22	83	WCIQ	TV	Mt Cheaha	AL	578
72	3	4	83	Anderson Comm	2W	Baldwin	ND	500
73	3	4	83	Capital Elec	2W	Baldwin	ND	200
74	3	5	83	KQDY	FM	Baldwin	ND	919
75	3	5	83	old tower	BK	Baldwin	ND	550
76	3	6	83	KXMC	TV	Minot	ND	1053
77	3	6	83	KSRE	TV	Minot	ND	1031
78	3	6	83	Souris River Tel	2W	Minot	ND	500
79	3	9	83	NW Cablevision	CT	Winchester	CT	
80	3	9	83	WCDC	TV	Mt Greylock	MA	247
81	3	11	83	WCSH	TV	Sebago	ME	1305
82	11	28	83	KWWL	TV	Rowley	IA	2000
83	3	18	84	KFDI	FM	Colwich	KS	1164
84	3	18	84	KLDH	TV	Dover	KS	1230
85	3	19	84	Council Grove	CT	Council Grove	KS	430
86	3	20	84	WVII	TV	E Eddington	ME	700
87	3	20	84	WABI	TV	Dixmont	ME	560
88	3	20	84	radio tower	2W	Dixmont	ME	40
89	3	4	85	State of SD	2W	Parker	SD	400
90	3	5	85	SPAT tower	TV	Fostoria	IA	435
91	12	1	86	NE G&P	2W	Bassett	NE	400
92	12	2	86	KMNE	TV	Bassett	NE	1524
93	12	2	86	NE Road Dept	2W	Rushville	NE	300
94	12	2	86	NE Road Dept	2W	Tryon	NE	270
95	3	18	87	State of SD	2W	Miller	SD	250
96	12	15	87	WWPZ	AM	Petoskey	MI	400
97	12	15	87	WAJC	FM	Indianapolis	IN	200
98	12	26	87	KTUL	TV	Coweta	OK	1906
99	1	7	89	WGMR	FM	Phillipsburg	PA	299
100	1	8	89	WBRE	TV	Mountaintop	PA	849
101	2	8	89	WSTZ	FM	Raymond	MS	1003
102	3	3	89	KFNF	FM	Oberlin	KS	450
103	3	8	89	WDSC	AM	Dillon	SC	
104	12	10	89	WPTF	TV	Auburn	NC	1929
105	12	10	89	WRAL	TV	Auburn	NC	2000
106	2	15	90	Falcon Cable	CT	Sedalia	MO	540
107	3	7	90	NE Road Dept	2W	Willowdale	NE	300
108	12	21	90	KHCD	TV	Manchester	KS	900
109	3	12	91	WSHW	FM	Middle Fork	IN	500
110	3	12	91	State of IN	2W	Geetingsville	IN	303
111	3	23	91	WDIO	TV	Duluth	MN	856
112	11	1	91	KIA	FM	Mason City	IA	812
113	11	1	91	KCMR	FM	Mason City	IA	445
114	11	1	91	CGordoCnty Sheriff	FM	Mason City	IA	250
115	11	1	91	KEZT	FM	Woodward	IA	1026
116	11	1	91	KNXR	FM	Rochester	MN	550
117	11	1	91	Falcon Cable	CT	Hiawatha	KS	480
118			92	Polk Cnty Sheriff	2W	Tryon	NC	50
119	3	18	93	Polk Cnty Sheriff	2W	Tryon	NC	50
120	2	10	94	WCLD	FM	Cleveland	MS	338
121	2		94	WDLJ	FM	Indianola	MS	
122	2		94	home 2W tower	2W	Clarksdale	MS	172
123	2	10	94	WAID	FM	Clarksdale	MS	327
124	2	10	94	WDMS	FM	Greenville	MS	500
125	2	10	94	Bolivar Cnty FD	2W	Pace	MS	198
126	2	10	94	WBAD	FM	Greenville	MS	300
127	2	10	94	WESY	AM	Greenville	MS	100
128	2	10	94	WIQQ	FM	Greenville	MS	530
129	2	10	94	KUUZ	FM	Greenville	MS	320
130	2	11	94	WSUH	AM	Oxford	MS	210
131	2	11	94	WMJW	FM	Cleveland	MS	399
132	2	11	94	WYMX	FM	Greenwood	MS	1029
133	2	11	94	Time Warner	CT	Cleveland	MS	420
134	2	11	94	Engelkes Farms	2W	Hamburg	AR	500
135	2		94	TN DOT	2W	Camden	TN	
136	1	22	95	WHCF	FM	Bangor	ME	575
137	2	5	96	WMUU	FM	Greenville	SC	200
138	2	5	96	WMUU backup	BK	Greenville	SC	80
139	2	5	96	WMUU 2W#1	2W	Greenville	SC	120
140	2	5	96	WMUU 2W#2	2W	Greenville	SC	120

TV = Television
FM = FM radio
AM = AM radio
CT = Cable TV
2W = Two-way radio

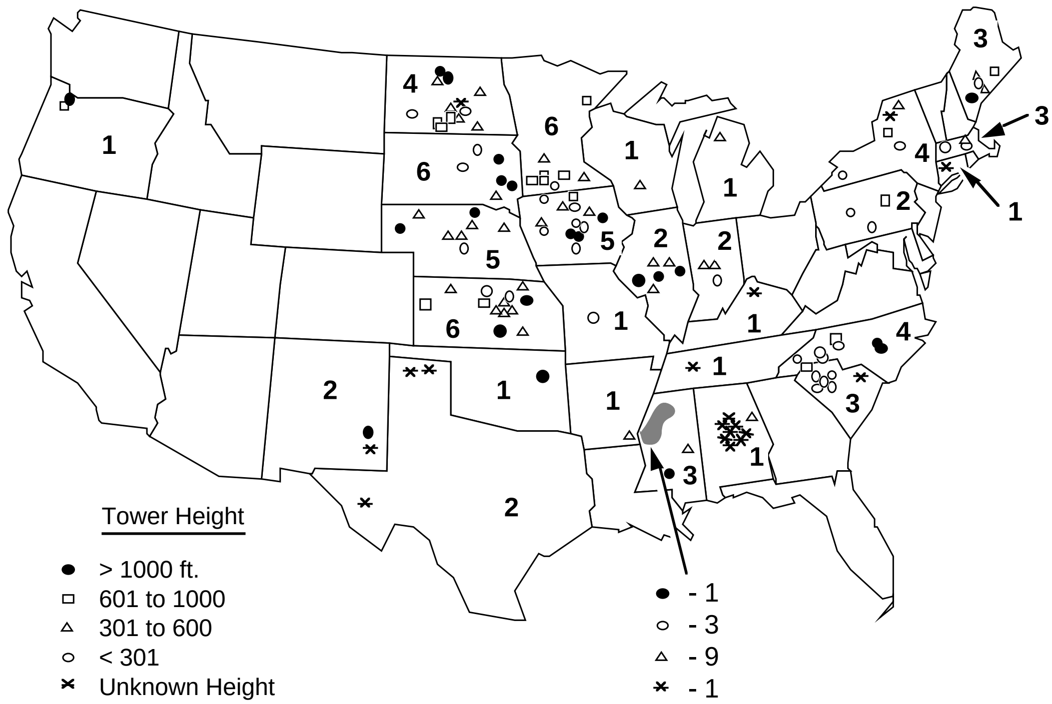


Figure 3. Icing-related tower failures since 1959. The boldfaced numeral in each state refers to the number of individual storms that caused the failures in that state.

ties collapsed. The 14 failures that I have confirmed to date for that storm are separately identified on the map. Many sources reported that these towers failed under radial ice thicknesses ranging from 4 to 6 in. Even though there was nearly no wind associated with that storm, the damage to trees, powerlines, and crops in Mississippi alone was estimated at more than $2 billion. The damage to eight of those towers, ranging from 172 to 530 ft tall with an average height of 344 ft, totalled nearly $1.8 million.

Other geographic and topographic information contained in this database includes the tower's coordinates, base elevation, height above average terrain (HAAT),* and a description of the terrain type upon which it was situated.

2.3 The Collapse

The database contains news and witness accounts of the collapse itself, such as the date and time of day, how the tower fell, how long after failure before personnel arrived to assess the damage, suspected cause of failure or whether a more formal engineering analysis was done to pinpoint the cause, and the maximum distance outward from the tower base that debris landed.

Figure 4 indicates that there have been several years in which major ice storms caused many failures over

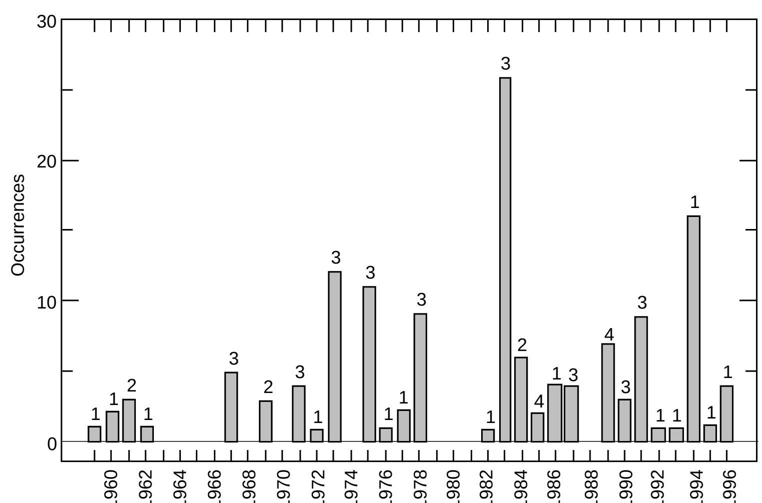


Figure 4. Histogram of failures by year since 1959. The numeral shown at the top of each column is the number of individual storms that caused the failures in that year.

* HAAT, or effective antenna height, is an industry term that describes a station's transmission coverage. To calculate HAAT, the ground elevation above sea level (asl) is averaged at fixed points between 2 and 10 air miles along eight radial lines extending outward from the tower base. HAAT is this average value subtracted from the asl height of the antenna's center of radiated power (Ennis 1979). HAAT might also be used as a relative measure of a tower's exposure to wind and clouds, and therefore, in-cloud icing.

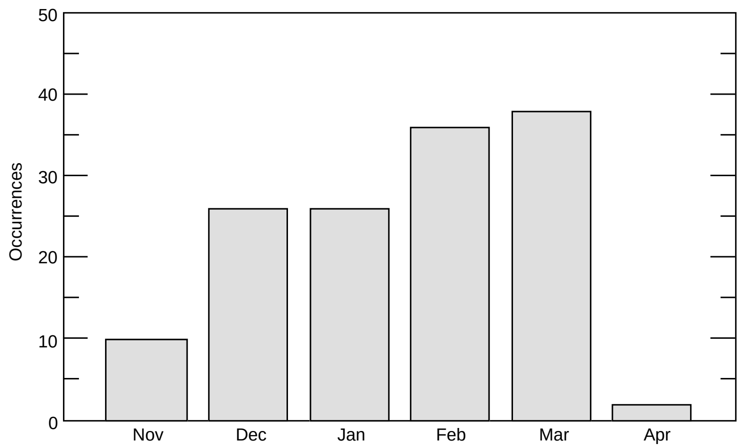


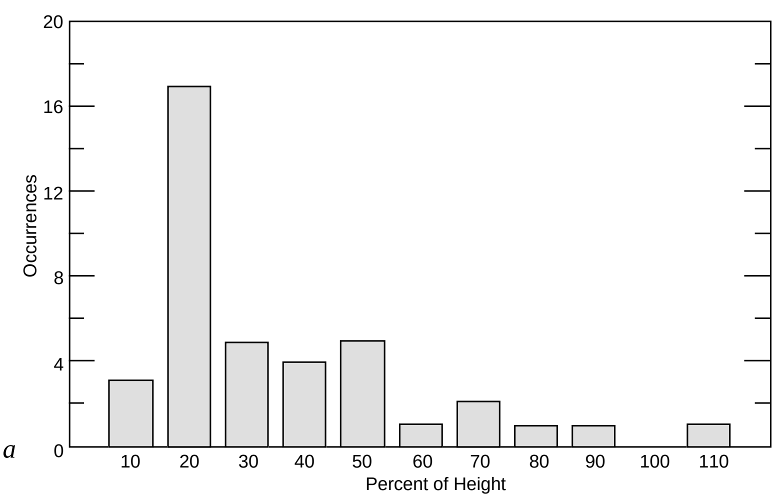
Figure 5. Histogram of failures by month.

widespread areas. Large storms in 1973, 1975, 1983, and 1994 caused 48 of the 65 confirmed failures in those years. For example, the 1973 total of 12 failures was the result of three separate storms, but 10 towers fell in Kansas and Iowa during a single large storm in December. The worst year was 1983, for which I have recorded 26 failures in three separate storms. Two storms, one in January and another in March, were responsible for all but three of them. The January storm caused heavy, widespread damage and brought down 15 towers across North and South Carolina, Alabama, and Mississippi. Seven more towers fell in North Dakota over a three-day period in March. One massive glaze ice storm was responsible for all 16 failures in 1994. The most storms that caused collapses in any one year was four, causing seven towers to fall in 1989.

The 'failure season' is December through March, as can be seen in Figure 5. I have recorded 26 failures in each of December and January, but February and March are the highest incidence months, each having about 37 failures. The relatively few November failures occurred throughout the month, whereas the two in April occurred on the last day of that month in 1967, in a late-spring storm of unusual intensity.

In 40 cases, station personnel estimated the maximum distance that debris landed out from the tower base. Though they may have underestimated the distance to downplay the danger, the data show that when towers fall, the debris is usually contained within a radius of 50% of the tower's height agl (Fig.6). The tensile strength of the guy cables relative to the bending strength of the tower members usually ensures that the tower will fold into shorter segments as it falls. This is especially true for buckling failures due to massive ice accretion and low wind conditions. The mean and median collapse radii for the 40 cases were 31 and 20%, respectively, and the standard deviation was 23%. Only six towers had a fall radius larger than 50%, and those were generally the result of unusual circumstances. For example, the 450-ft WKOX tower in Massachusetts reportedly jumped 5 ft off its base and laid out full length on the ground when 80-mph winds caused the cable grips on an insulator to fail. Cable grips failed in several other cases but the towers always folded into a smaller radius. In the case of the

Figure 6. Histogram of collapse radius as a percent of tower height.



1164-ft KFDI tower in Kansas, only the top 79 ft of the tower fell when melting ice slid down a guy cable and smashed the cable grip at the anchor. As the top fell, it became entangled in a lower guy cable and slid down its length all the way to an outer anchor, resulting in a 60% collapse radius.

Although many failures occurred without warning and with station personnel on site (28 of 82 sites were known to be manned at the time of failure), only two resulted in injuries to station employees. There have been no injuries to passersby. The worst injury occurred in 1960 at a remote site in New Mexico when the 1610-ft KSWS tower fell onto the transmitter building in which four people were working, one of whom suffered a broken knee. Three other buildings, which housed the employees' families, were damaged by falling debris, but no one in them was injured. The second injury occurred in the 1983 collapse of the 578-ft WCIQ tower atop Alabama's highest point, Mt. Cheaha. The transmitter technician sustained minor cuts while climbing out of the debris after the collapse. In earlier years, many transmitter sites were manned, but that is less common with today's more automated equipment, reducing the risk of employee injury in the future.

2.4 Concurrent weather

I made a qualitative appraisal of the on-site weather and ice conditions prior to tower collapse, using any or all of these four sources: 1) interviews with station personnel, 2) local newspaper articles, 3) *Storm Data* (NOAA 1959–1995), and 4) meteorological data from nearby weather stations. During my interviews with station personnel, I obtained their subjective estimates of the ground level wind speed, tower ice thickness and ice type. Newspaper articles about a collapse often provided additional qualitative information on tower conditions. *Storm Data* provided a county-specific overview of the storm conditions, the storm's progression, and its consequences. *Storm Data* also mentioned many tower failures that I had not previously known of, which were, in turn, researched and added to the database. I also used NCDC's *Local Climatological Data* publications, which provided quantitative meteorological measurements at nearby weather stations; I interpolated or extrapolated these to the collapse site.

My preliminary analysis suggests that most confirmed icing-related tower failures in the southern U.S. were the result of a few very large and very severe storms. All of the confirmed failures in the south (47 of 140) resulted from only 12 separate storms, whereas the 93 failures in the north occurred during 48 distinct storms.

The ice that destroyed towers in southern storms was more frequently the result of freezing precipitation from, for example, freezing rain and drizzle (Table 2). Of the 30 incidents occurring in the south for which ice type has been determined, 20 (67%) were the result of precipitational icing. Regions farther north experience lower temperatures for longer periods, so that in-cloud icing, or rime icing, is more prevalent (54 of 90 cases [60%] involved rime or a rime-glaze mix).

Table 2. Frequency of failures associated with ice type and wind speed.

Icing source	*Southern U.S.**	*Northern U.S.**
Precipitation	20	36
In-cloud	2	36
Mixed	8	18
Estimated wind speed (mph)	***Central plains*†**	***All other regions***
Low (< 10)	37	20
Med (10 to 30)	13	12
High (> 30)	15	23

* Northern and southern U.S. as divided by latitude N37°.

† Including the states of Illinois, Minnesota, Iowa, Missouri, Oklahoma, Kansas, Nebraska, North Dakota and South Dakota.

Failures in the central Great Plains more frequently occurred at low wind speeds. Fifty-seven percent (37 of 65) of those cases happened when the estimated winds were less than 10 mph, whereas only 36% (20 of 55 cases) in all other areas of the country were accompanied by such low winds.

Figure 7 shows the distribution of the factors that contributed to these failures. In most cases, I assessed the available wind and ice load information to determine the cause of failure; however, in a few cases other specific factors were cited. For example: a tower fell after being hit by an adjacent tower that fell; a gin pole used for tower construction was in place near the top of the tower (causing catastrophic imbalance when loaded with ice or wind-on-ice); or the tower was galloping (oscillating severely) under the combined wind and ice loads. Six failures were directly attributable to ice shedding under warming conditions. That is, either a cylindrical piece of ice slid down a guy and destroyed the cable grip at the anchor, or the sudden release of ice induced a catastrophic load imbalance.

When possible, I categorized the failures based on an assessment of the ice and wind loads derived from available information. I classified each failure as resulting primarily from ice load (if there was little wind and much ice), wind load (if there was much wind but little ice), or wind-on-ice load (if both were probably important). Note that this categorization does not take into consideration the specific loads that the towers were

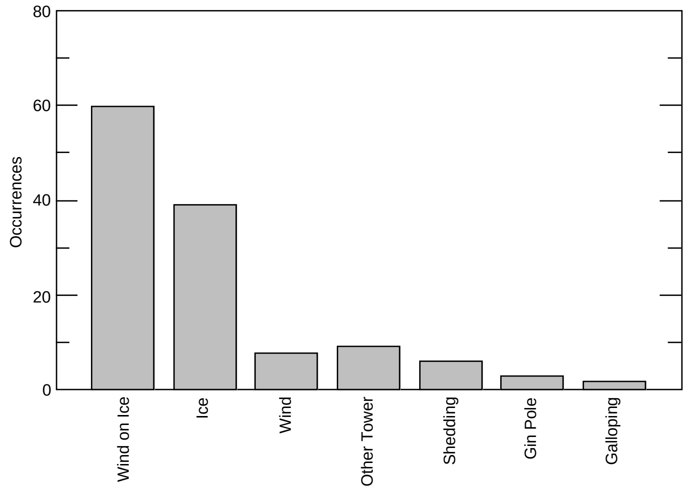


Figure 7. Histogram of factors leading to collapse.

designed for. In general, whenever the wind was greater than 10 mph, I concluded that wind was a factor, either by itself or in combination with the estimated iceload. As shown in the Figure 7, 56% of the failures that could be categorized (60 of 106) were associated with combined wind-on-ice load. In 37% of cases (39 of 106), I judged ice load alone to be the primary cause. In only seven failures do I believe that severe wind was instrumental and that the ice load was incidental to the failure.

2.5 Damage

For each failure, I attempted to document the type and estimated cost of property and business losses, whether injuries occurred, how long each owner was completely off the air, the percentage of original transmission area that was restored with a temporary antenna, and how long it was before the station was finally operating normally.

When a tower falls, the initial damage usually includes the complete loss of the tower and everything on it, and often includes damage to the transmitter and electrical feed housed at its base. Falling debris damages equipment both on- and off-site, including commercial and residential buildings, vehicles, electrical transmission lines, and crops. In addition, the costs to commercial and public broadcasters accrue in the form of lost advertising revenue until the station is able to return to the air. The advertising rates that a station charges are based on the size of its listening or viewing area. This loss information is generally proprietary, because of the highly competitive nature of the industry. So important is maintaining market share that owners need to return to the air as soon as possible. This is usually done by installing a temporary, limited-coverage facility to serve until a permanent one can be reconstructed. Getting back on air requires paying a premium for overtime wages and restoration services which include damage assessment, cleanup, setup of temporary equipment, design of the new facility, applying for federal and municipal approvals, site preparation and, finally, reconstruction. Employees are sometimes laid off for months. In the 56 cases in which I have an estimated time for the station's return to normal operation, the average was 196 days and the standard deviation was 150 days. Three cases required more than 540 days to return to normal operations, 16 cases required 300 or more days, and one station was bankrupted and returned to the air under a different owner. The monetary damage can be enormous.

The database currently contains damage estimates for 73 of the 140 failures, which ranged between $4000 in 1959 to $10 million in 1989, and averaged more than $713,000. The standard deviation, though, was more than $1.5 million, indicating a large spread in the data, which can be attributed to 1) differences in the types of costs that were accounted for, 2) the wide range of sources from which the estimates were obtained, 3) no attempt to adjust for monetary inflation, and 4) some cases that involved only a partial collapse of the tower and therefore less damage. As one would expect, costs increase with tower height and this relationship is shown in Figure 8. The wide range in the estimated costs for all tower heights is best shown in semi-log form.

Losses from a single tower failure have run as high as $10 million. Two 2000-ft television towers at the same site outside Raleigh, North Carolina, fell approximately 1 hr apart in December 1989. Witnesses said that the wind was calm and the sun had come out after a severe sleet and freezing rain storm. When chunks of ice, some weighing an estimated 600 lb, began shedding from the warmed steel, reactional oscillations caused the heavily loaded structures to buckle. An insurance industry source

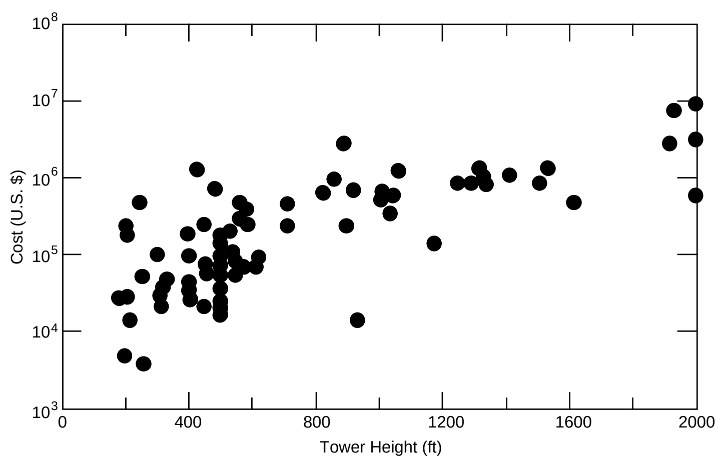


Figure 8. Damage costs as a function of tower height.

revealed that losses related to the first tower totaled $8 million, while the second cost the insurer another $10 million.

3. Possible Future Work

The database is as yet incomplete. Interviews have been completed for only 60% of the failures, newspaper articles have been obtained for only 70%, and an analysis of the weather data is complete for only 60% of cases. Several failures are still unconfirmed. At this time, CRREL does not have a mandate or the funding necessary to continue significant research effort on this subject. However, further work is needed and includes:

1. Research of the total numbers of various tower types in the different states or regions of the country to gain a better understanding of rates of failure;
2. Retrieval and analysis of meteorological data to profile better the typical storm conditions that cause towers to fall;
3. Where higher-risk locations are found, examine whether the ice and wind-on-ice design loads are adequate;
4. More-detailed analysis of damage costs to understand better the relationships between damage and parameters such as tower type, height, age, base elevation, icing type, wind speed, and so forth.

4. Summary of Findings

CRREL has an established database of icing-related communication tower collapses for the U.S. This database reveals where and when icing-related tower collapses have occurred in the United States. The record contains information dating back to 1959 on the failures of 140 towers, including radio, television, microwave, and two-way towers. Information was compiled from interviews with tower engineers, owners, station personnel, and others, from local newspaper articles, monthly storm publications, and digital databases maintained by the USGS and NOAA. For each failure, I am compiling information on the tower structure and its geographic location, the collapse sequence, the concurrent weather, and the resulting damage. The information is incomplete, although a summary is as follows:

Structural characteristics

- The largest number of failures involved FM, television, and two-way towers.
- Of the 121 towers for which we have height data, one-third were under 300 ft tall, another third were between 300 ft and 601 ft, and one-fifth were taller than 1000 ft.
- Only one tower was known to be freestanding.
- The mean age of 77 towers that fell was 11.5 yr.

Geographic location

- Most of the failures occurred in the midwestern states and the Appalachian highlands.
- All except two failures occurred east of the Rocky Mountains.
- Two-thirds occurred north of latitude N37°.
- The failures in the southern U.S. are generally the result of fewer, but more severe, storms than those in the midwest.

Collapse

- Large storms in 1973, 1975, 1983, and 1994 caused 48 of the 65 failures that occurred during those years.
- The worst single year was 1983, in which 26 failures occurred.
- The most storms that caused failures in any one year was four, in 1989.
- More than 90% of the failures occurred between December 1 and March 31.
- When a tower falls, the debris is usually contained within a radius of 50% of the tower's height.
- Two failures have caused minor injury. There have been no serious injuries, and no passersby have been injured.

Concurrent weather

- Twice as many towers fell in four times as many storms in the northern U.S., compared with the southern U.S.
- Sixty-seven percent of the failures occurring in the south were the result of precipitational icing, whereas 60% of northern failures involved in-cloud icing.
- Fifty-seven percent of failures in the Great Plains occurred under low wind speed conditions, compared with 36% for all other areas of the country.
- I judged wind-on-ice loading to be instrumental in 56% of 106 failures, ice loading alone to be instrumental in 37% of cases, and wind loading alone (icing was incidental) in 7% of cases.

Damage

- The damage caused by tower collapse is both immediate and delayed in nature. Immediate costs include the loss of the tower and equipment on it, but also may include buildings, equipment, vehicles, the transmitter, power lines, and other adjacent property. Delayed costs include lost advertising revenue while the station is completely or partially off the air, employee layoffs, higher costs for restoration services, and overtime wages.
- The estimated mean time required for 57 stations to return to normal operations after a collapse was

196 days. Three cases required more than 540 days and 16 required 300 or more days.

- Damage costs for 73 failures, shown to increase as a function of tower height, averaged more than $713,000, although the standard deviation was large, due to lack of data refinement.

Acknowledgements

The author wishes to thank Kathleen Jones and Michael Ferrick of CRREL's Snow and Ice Division for their technical reviews and many helpful suggestions, David Fisk for editorial review, Matthew Pacillo for illustration preparation, and Donna Valliere for manuscript production.

References

Duvall, V.G. (1993) Telecommunications Group, Inc., Friendswood, Texas, personal communication.

Ennis, H.E. (1979) *Television Broadcasting: Equipment, Systems, and Operating Fundamentals*. Indianapolis: Howard W. Sams & Co., Inc, 2nd ed., p. 540–542.

FEMA (1994) Hazard mitigation survey team report in response to: The February 18, 1994 Federal Disaster Declaration for the State of Mississippi. Federal Emergency Management Agency, FEMA-1009-DR-MS.

Goudy, C. (1992) Structural Systems Technology, Inc., McLean, Virginia, personal communication.

Laiho, J. (1993) Finnish Broadcasting Company, Helsinki, Finland, personal communication.

Lott, N. and T. Ross (1994) 1994 weather in the southeast; The February ice storm and the July flooding. National Climatic Data Center, Technical Report 94-03, October 12, 1994.

Marshall, D.G. (1992) LeBlanc & Royle Telcom, Inc., Oakville, Ontario, Canada, personal communication.

Monts, D.E. (1992) Kline Towers, Columbia, South Carolina, personal communication.

NCDC (1960–1994) Local climatological data monthly summary (for selected U.S. cities). National Climatic Data Center, Asheville, North Carolina.

NOAA (1959–1995) Storm data and unusual weather phenomena with late reports and corrections. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina.

O'Brien, K. (1994) U.S. Dept. Of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Coast and Geodetic Survey, Rockville, Maryland, personal communication.

USGS (1995) GNIS: Geographic Names Information System [CD-ROM]. U.S. Geological Survey, Reston, Virginia, Sept 1993.

APPENDIX: SURVEY FORM USED TO RECORD INFORMATION OBTAINED DURING TELEPHONE INTERVIEWS

Each question is more fully described by the italicized notation following it

TOWER COLLAPSE SURVEY SHEET (*Key)*

TOWER IDENTIFICATION: **Boldfaced items are most important**

Tower name: *Station call letters, e.g.,"WTSL-FM"* Owner or studio address/telephone:	Interviewer: Date: *Of interview* Interviewee name/title/telephone: 1st- or 2nd-hand info?: *To indicate accuracy of info, e.g., eyewitness to event? employed at station at time?*

TOWER LOCATION/SITE DESCRIPTION:

Tower location: *e.g., "3 mi south of I-89 on Rt 12A", or "top of Big Mt", or "at intersection of Elm and Main St."*	**Coordinates: N_____________ W_____________**	
Location description: *e.g., mountaintop, open fields, forested, urban, high plains*	**Base elevation (asl):**	**Top elevation (asl):**

FAILURE DESCRIPTION:

Date and time **of failure:** **Suspected cause of failure:** *e.g., "Light rime icing caused by low cloud ceiling followed by clearing skies and increasing wind. Top NE guy attachment on the tower finally broke after 2 hr of continuous cable galloping."* Witnessed; or how long after did someone arrive on site? *To indicate what confidence we can have in the estimation of the ice and wind at the time.*	Engineering post mortem done? *Formal report available?* Description of failure event: e.g., *"Broken guy wire allowed the main antenna to snap off. Antenna snagged and slid down a lower guy, breaking the anchor attachment. Top 300 ft of tower then fell to the SW, bottom 500 ft fell to N."* How long after collapse did an engineer arrive on site? *To indicate what degree of confidence we can have in the estimation of the failure mechanism.*
Max distance that tower debris landed from base? **Estimated windspeed:** *At or about time of failure* **Icing source?** *In-cloud or precipitational*	**Estimated ice thickness and type:** *e.g., "max. 1-in. radial rime on upper 300 ft of guys", or "6 in hard rime at top N side entire tower dminshing to 1 in at 600-ft level"*

TOWER DESCRIPTION:

Tower manufacturer/model:	**Age:** *Year erected*	**Face width:** *Of tower, or various widths and elevations of taper points*
Guy levels: *# of elevation points where guys attach to tower*	**Anchor pattern:** *Ground pattern of guy system*	Ice protection: *Heaters, radomes, wide-band antenna, other*
Design load specs: *For wind and ice*	Other equipment/antennas on tower:	
Tower height (ft):	Antenna height (ft):	HAAT (ft): *Height above avg terrain**

** HAAT, a radio and tv broadcasting term, is a measure of an antenna's effective height above the surrounding terrain*

DAMAGES:

100% off air time: *How many weeks, months*	**% coverage w/ emerg equip:** *% of normal broadcast area*	**Normal ops returned when?** *How many weeks or months*
Describe equipment/adjacent property losses and est costs: *Est of total costs if breakdown not available*	*e.g., losses to tower & equipment, fencing, buildings, vehicles, advertising revenue, labor, etc.*	**Injuries?**

OTHER CONTACTS:

1. *e.g., tower manufacturer's rep*
2. *local newspapers*
3. *insurance company*
4.

Location, date **and call letters of other collapses:** *Any communication tower, incl AM, FM, TV, microwave, cellular, two-way; either in the same vicinity or elsewhere, same or separate storm.*